Flexible Multibody Dynamics of Deployable Wing Aircraft

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論文内容要約

Next-generation deployable aerospace structures have many bodies and joints to enable both a large surface area in the deployed state and compactness in the folded state. These structures are very flexible because of their light weight. The system is referred to as "Flexible Multibody System" because it consists of many deformable bodies and various joints to connect the bodies.

Deployable wings are classified in the flexible multibody systems. The deployable wings that can be deployed or folded in span direction during flight have become attractive recently because they have the potential to improve the ability of aircraft drastically. Several reasons why the deployable wing is attractive are listed below.

- The wing aspect ratio of the commercial aircraft is increasing to reduce the induced drag effect, and thus the wing needs to have a deployment/folding system to meet the airport gate size. The future commercial aircraft designs, such as Boeing SUGAR and 777-X have the deployable wing.
- The wing deployment system can be used for the stability enhancement, flight control, gust load alleviation, and the adaptivity for various missions.
- The wing deployment system is useful for the unmanned aerial vehicle (UAV) with monitoring and exploration missions.
- The lightweight and powerful actuator technology has been developed recently.

In the 2000s, Japanese Aerospace Exploration Agency (JAXA) proposed a deployable wing aircraft to conduct a Mars exploration. A spacecraft and a rocket are generally utilized as carriers to take the Mars-airplane from Earth to Mars. However, the carriers do not have a large storage space to store the airplane. Thus, the Mars-airplane requires deployable wings to save storage space. The wing achieved both a large surface area to fly on Mars and compactness for storing the aircraft in a narrow space. The wing should be thin to obtain a good aerodynamic performance in the Martin atmosphere. Therefore, the deployable wing has a possibility to deform largely. Since 2016, NASA has engaged in the spanwise adaptive wing (SAW) project to apply the deployable wing to supersonic commercial aircraft. This is because the recent actuators for the deployment and folding become lightweight and powerful, and thus the folding wing has become more feasible than the past. In 2018, NASA succeeded in the test of the in-flight wing folding using a small experimental model. Recently, high altitude long

endurance (HALE) aircraft has become attractive for the purpose of disaster monitoring and telecommunication. The HALE aircraft generates a propulsive force using solar panels on the wing surface. To increase the solar energy, the wing is folded and deployed to turn the solar panels on the sun.

In designing the deployable wing, various computer simulations using numerical models are necessary for reducing the cost and time of the design and development. Structural, aerodynamic, and aeroelastic simulation models have been proposed. However, the establishment of the deployment simulation model is still an open problem because the deployable wing causes a complex motion comprising large rigid body rotation around a joint and aeroelastic deformation. Multibody dynamics (MBD) is a suitable theory for modeling the deployable wings. MBD models various joints systematically. To consider the flexible deformation of bodies, MBD is coupled with a nonlinear finite element method (FEM). Although the FEM limited to small elastic deformation has been used for modeling the deployable wing so far, it is not suitable for the future aircraft that causes extremely large aeroelastic deformation owing to its lightweight, high aspect ratio, and small wing thickness.

In this thesis, absolute nodal coordinate formulation (ANCF) is adopted to express the large elastic deformation. ANCF is a recently attractive nonlinear FEM because of its many advantages. The mass matrix is constant. The imaginary forces are not needed to be considered. The joint conditions are written simply. The strain is exactly zero under a pure rigid body motion. A wide variety of ANCF elements, such as beam, plate, and solid elements, have been proposed. However, the ANCF elements have not been applied to aircraft because of four problems.

First, the frequency-domain aeroelastic simulation for the deployable wing is difficult to be performed because the ANCF elastic force has a strong nonlinearity, and thus it is not easy to linearize the elastic force.

Second, a three-dimensional (3D) ANCF beam element cannot be applied to complicated cross-sectional structures such as a wing. In the general dynamic simulation of a wing using beam theory, the cross-sectional properties are obtained from cross-sectional analysis to derive the elastic force. However, because the 3D ANCF beam element compulsorily expresses cross-sectional deformations, the cross-sectional properties cannot be used to derive the elastic force.

Third, the lack of the deployment system models prevents the ANCF elements from being used for the deployment simulation. The deployment system is composed of an actuator generating torque around a hinge axis, a holding/releasing mechanism, and a latching mechanism. This lack of the deployment system models is attributed to the difficult definition of the relative rotation angle around the hinge axis between jointed bodies in ANCF. Only vectors expressed in a global coordinate system are used as the generalized coordinates in ANCF, and thus the rotation angle definition is difficult. Although the characteristic of ANCF to express large motion has been mainly focused on, another important characteristic to describe the constraint condition in a simple form has not been fully taken advantage of. This simple description is useful for the holding/releasing mechanism modeling.

Fourth, the ANCF plate elements are inferior to the ANCF beam elements in terms of the computational time because the degrees of freedom increase, although the ANCF plate elements can express complicated motion and multiple joints more easily than the ANCF beam elements. Therefore, the calculation time reduction is a problem that need to be solved for the ANCF plate elements.

In this thesis, deployable wing modeling methods based on ANCF are proposed by solving the abovementioned problems. This study has four objectives.

The first objective is to propose a versatile model that can be applied not only to the time-domain but also to the frequency-domain simulations. A nonlinear model is first derived using a 2D ANCF beam element with a new torsional degree of freedom for the time-domain deployment simulation. The expression of such coupled motion was completely impossible in the past deployable wing research. Then, to apply the model to the frequency-domain flutter analysis, the proposed nonlinear model is linearized. To overcome the difficulty in linearizing the ANCF model, the nonlinearity of the ANCF elastic force is mitigated by assuming that the axial deformation is smaller than the bending deformation. This mitigated nonlinearity not only helps to facilitate the linearization process but also helps to reduce the calculation time required for the time-domain deployment simulation.

The second objective is to propose a 3D ANCF beam element that can be applied to wings. To achieve this objective, an elastic force formulation is proposed based on element coordinate approach, Frenet–Serret equation, and internal constraint equations (ICEs). ICEs generally used for rigid body modeling restrict internal deformation, whereas external constraint equations (ECEs) can represent mechanical joints. The new elastic force formulation provides a 3D ANCF Euler–Bernoulli beam element without the cross-sectional deformation that is not dominant in the deployable wing motion. The proposed formulation is named as absolute nodal coordinate formulation with internal constraint equation (ANCF-ICE).

The third objective is to propose a deployable wing modeling method based on the ANCF plate elements. In the proposed model, the two problems mentioned above are solved. The actuator torque is modeled by focusing on the characteristic of the deployable wing. The characteristic is that the in-plane deformation is much smaller than the out-of-plane deformation. By leveraging this characteristic, a local joint coordinate system is newly defined to model the actuator torque in this thesis. Consequently, we can calculate the actuator torque, even when the hinge axis performs an arbitrary 3D motion having relative rotation angles. The holding/releasing mechanism is modeled by switching the constraint conditions in a time integration process. This is accomplished by taking advantage of the simple constraint condition due to the advantage of ANCF. Additionally, the latching mechanism is modeled by instantaneously increasing the stiffness of the torsional spring attached to the hinge joint. The holding/releasing/latching timing is determined by using the relative rotation angle calculated by using the proposed local joint coordinate system. The forth problem, namely the long calculation time of the ANCF plate elements, is solved by introducing the small in-plane deformation assumption. We can model the elastic force in terms of the out-of-plane deformation in a linear form. By using the linear elastic force, a modal reduction technique can be used to reduce the calculation time.

The fourth objective is to experimentally validate the deployment simulation using the proposed model. In the past, there was no experimental data to validate the deployment simulation especially when the wing has a flexible property. Therefore, wing deployment experiments are conducted in a wind tunnel at Institute of Fluid Science, Tohoku University.

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